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CRUISE MISSILE PROLIFERATION: AN
APPLICATION OF BAYESIAN ANALYSIS
TO INTELLIGENCE FORECASTING

by

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This thesis examines the manner in which the technique of Bayesian analysis may be applied to the forecasting of cruise missile proliferation. Bayesian analysis is a quantitative procedure in which the alternative hypothetical outcomes are postulated and their prior probabilities estimated. As additional relevant events occur, the probabilities of their association with each hypothesis are used to calculate a revised probability for each alternative outcome. To support a sample analysis, this thesis traces the historical development of cruise missiles, discusses the various motivations for their acquisition or indigenous production by a developing nation, and identifies technologies crucial to the building of an advanced cruise missile system. After describing the Bayesian method and demonstrating its use in a theoretical example, the thesis concludes with some policy implications of cruise missile proliferation and its forecasting by the intelligence community.

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Cruise Missile Proliferation: an Application of Bayesian Analysis to Intelligence Forecasting

by

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ABSTRACT

This thesis examines the manner in which the technique of Bayesian analysis may be applied to the forecasting of cruise missile proliferation. Bayesian analysis is a quantitative procedure in which alternative hypothetical outcomes are postulated and their prior probabilities estimated. As additional relevant events occur, the probabilities of their association with each hypothesis are used to calculate a revised probability for each alternative outcome. To support a sample analysis, this thesis traces the historical development of cruise missiles, discusses the various motivations for their acquisition or indigenous production by a developing nation, and identifies technologies crucial to the building of an advanced cruise missile system. After describing the Bayesian method and demonstrating its use in a theoretical example, the thesis concludes with some of the policy implications of cruise missile proliferation and its forecasting by the intelligence community.

EXECUTIVE SUMMARY

Unmanned aerodynamic guided weapons, also known as cruise missiles, have existed as a concept since the invention of the airplane. In the last thirty years, a series of technological breakthroughs in propulsion, guidance, warhead and stealth technology have made the cruise missile a potent offensive strike weapon. The successful use of Tomahawk and AGM-86C cruise missiles by the United States against Iraq in the Persian Gulf war, as well as the dissolution of the Soviet Union, guarantee that cruise missiles and cruise missile technology will be both desired by, and available to, a number of developing nations.

The purpose of this thesis is to propose a forecasting technique by which the proliferation of modern cruise missiles, and the transfer of sophisticated missile technology, may be predicted, monitored and evaluated.

The forecasting technique described herein, Bayesian analysis, has been used by the Central Intelligence Agency for politico-military purposes; specifically, to provide Indications and Warning (I&W) of the possible outbreak of armed conflict. Bayesian analysis uses the assumption that an observed event has varying probabilities of occurring depending on the truth of alternative causative hypotheses. Over time, by observation and probabilistic evaluation of many

events, the "posterior probabilities" of each hypothetical cause will be driven toward either zero (not likely to occur) or one (very likely to occur).

This thesis addresses the context in which specific events relating to cruise missile proliferation and indigenous production may be evaluated. Major topics include:

1. The historical context of cruise missile employment.

2. The present state of the art of operational cruise missiles (i.e., the Tomahawk).

3. The various motivations which might drive a lesser developed nation to acquire, build or deploy modern cruise missiles. These motivations include international prestige, accelerated industrialization, military necessity, and economic benefits.

4. The technologies, possession of which are essential to the construction of a survivable, reliable and effective cruise missile. Among these technological categories are stealth, airframe and propulsion systems, guidance systems, and warheads.

5. The nature of the database which would be required to conduct a Bayesian analysis involving the forecasting of cruise missile proliferation.

A theoretical case study demonstrates the advantages and drawbacks of Bayesian analysis with respect to intelligence forecasting. **The principal advantage of the method is the establishment of a formal analytical framework which**

accommodates weighted inputs of all observed events, makes differing interpretations of a given event more explicit, and provides a readily available chronological record of the analytical process. The use of this technique is limited, though, to situations which can be expressed as a number of mutually exclusive outcomes. An ample flow of data which is logically related to the hypotheses to be tested must be available, and analysts must be qualified to assign realistic probabilities associating the observed events to their hypothetical causes.

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I INTRODUCTION

On January 17, 1991, over 100 Tomahawk land-attack cruise missiles (TLAMs) were launched by United States warships against targets in Iraq. Over the next three weeks, nearly two hundred more TLAMs, armed with either unitary high-explosive warheads or combined effect packages of submunitions, were launched in follow-on strikes. [Ref. 1:pp. 37-47] By some accounts, 85 percent of these sophisticated weapons successfully struck their targets [Ref. 2:pp. 71-73]. The U.S. attack ushered in a new era in cruise missile technology: for the first time, cruise missiles[1] with conventional warheads had been employed, successfully and in large numbers, to attack point targets ashore at over-the-horizon ranges.

The apparent ease with which American cruise missiles penetrated a sophisticated, Soviet-design integrated air defense system (IADS) suggests a disturbing corollary. Other cruise missile systems may exist, or soon may be developed,

[1] The precise definition of "cruise missile" is open to debate. The working definition adopted for this paper is from Kosta Tsipis's article, "Cruise Missiles," which appeared in the February, 1977 Scientific American: "a dispensable, pilotless, self-guided, continuously powered, air-breathing warhead-delivery vehicle that flies just like an airplane, supported by aerodynamic forces." As noted in Huisken, The Origin of the Strategic Cruise Missile, this definition excludes rocket-propelled weapons like the French Exocet and the Soviet Styx. Such weapons will be discussed, however, in recognition of the absence of a universally accepted definition of cruise missiles.

which could penetrate, as easily and as effectively, an American air defense system ashore or afloat. The manner in which such missile systems might be identified, and their developmental status monitored, is the subject of this thesis.

Cruise missiles have been used in combat since World War II.[2] They have been built for both strategic and tactical applications, and fitted with nuclear as well as conventional warheads. Air-, sea-, and ground-launched cruise missile systems have been designed and built. The potential value of anti-ship cruise missiles, in particular, was suggested as early as 1967 with the sinking of the Israeli destroyer EILAT by an Egyptian SSN-2 Styx missile [Ref. 3:p. 29]. Yet, since the late 1950s, the threat posed by cruise missiles has been overshadowed by the existence of ballistic missiles: specifically, by the adoption of intercontinental ballistic missiles (ICBMs) and submarine-launched ballistic missiles (SLBMs) as the primary unmanned strategic (nuclear) deterrent weapons of both the Soviet Union and the United States.

There are several good reasons why ballistic missiles, rather than cruise missiles, were adopted for the role of strategic strike. Ballistic missiles traveled intercontinental ranges much more quickly than cruise missiles and they were capable of achieving far greater accuracy than

[2] The concept of an unmanned "flying bomb" dates back to the dawn of the flying age, prior to World War I. For a concise history of early cruise missile development attempts, see Kenneth P. Werrell, The Evolution of the Cruise Missile, Chapter 2. Werrell cites references as early as 1892.

inertially-guided cruise missiles [Ref. 3:p. 18]. Ballistic missiles also would be much harder to shoot down than aircraft-sized cruise missiles, whereas smaller (and therefore more survivable) cruise missiles would have been unable to carry nuclear warheads sufficiently large to accomplish their prescribed strategic missions (given the inherent inaccuracy of inertial guidance at intercontinental ranges).

Now, however, advances in propulsion, guidance and warhead technologies have led to the re-emergence of the cruise missile as a versatile and effective long-range strike weapon. Small, efficient turbofan engines, coupled with improved inertial guidance systems and a variety of midcourse and terminal position updating capabilities, have made possible the accurate delivery of highly destructive payloads.

This capability, epitomized by the Tomahawk land-attack missile, no longer resides exclusively with the United States and its defense establishment. Several other nations, if sufficiently motivated, could soon field a "modern" (i.e., reliable, accurate and survivable) land-attack cruise missile. At least a few of these nations undoubtedly will do so. Seth Carus, author of Ballistic Missiles in the Third World, expressed his opinion on cruise missile proliferation:

> It is the cruise missile, however, that will pose the most serious challenge in the 1990s. The technologies required to build conventionally armed cruise missiles will be within the reach of a considerable number of countries in the Third World.

> Cruise missile guidance systems will be readily available....mak[ing] it possible for cruise missiles to achieve accuracies of less than 100 meters, even at long ranges....Tied together with cluster munitions, intelligent submunitions, and fuel air explosives, **cruise missiles will have the accuracy and lethality to be extraordinarily effective**. [Ref. 4:p. 39; emphasis added]

Anti-ship cruise missiles (ASCMs) are also almost certain to proliferate. The Soviet Union has fielded operational air-launched ASCMs since 1958 and sea-launched ASCMs since 1960 [Ref. 5:pp. 157-8].[3] Improved systems have appeared regularly. Even after the August 1991 coup attempt, work reportedly continued on a next-generation Soviet sea-launched ASCM, the SS-NX-25 [Ref. 6:p. 348].

The United States countered Soviet anti-ship cruise missile developments by deploying the Harpoon weapon system in 1977 [Ref. 7:p. 233] and the anti-ship variant of the Tomahawk, the TASM,[4] in 1983 [Ref. 8:p. 193]. Significantly, while ASCM development has proceeded apace, anti-ship missile defenses have lagged. The British experience in the Falklands War and the 1987 STARK incident vividly demonstrated the threat to naval forces posed by small, sophisticated, guided

[3] The nuclear-armed SS-N-3c Shaddock was first tested in 1954, and deployed aboard Whiskey and Echo I class submarines beginning in 1960. The dual-capable (i.e., nuclear and conventional) SS-N-3a Shaddock and the surface-launched SS-N-3b Sepal variants both entered service in 1962. The first Soviet air-launched ASCM was the conventionally-armed AS-1 Kennel (1958). The nuclear-capable AS-2 Kipper followed in 1961. [Ref. 5:pp. 157-8]

[4] TASM: Tomahawk Anti-Ship Missile

weapons.[5] In fact, the U.S. Navy's Assistant Chief of Naval Operations for Surface Warfare [ACNO(SW)] recently declared missile defense to be "a top modernization priority within the...surface warfare community," surpassing even anti-submarine warfare (ASW), which long held the top position on such lists. [Ref. 11:p. 437]

A U.S. Navy aircraft carrier battle group (CVBG) in the open ocean, defended by Aegis and New Threat Upgrade (NTU) cruisers and long-range combat air patrol (CAP) aircraft, is probably quite well protected against (although not invulnerable to) anti-ship cruise missile attacks. An amphibious task group approaching the coastline of some new Third World trouble spot is not. Similarly vulnerable to land-attack cruise missiles are the headquarters of a Marine Expeditionary Group or other military force ashore, their debarkation sites, and their airfields. During Operation DESERT STORM, for example, Iraqi cruise missiles (had they existed) could have been employed against the U.S. Central Command headquarters compound in Riyadh, against the port facilities at Al Jubayl, or against coalition air bases such

---

[5] In 1982, Great Britain and Argentina waged a military campaign for possession of the Falklands (Malvinas) Islands in the South Atlantic. Two British ships, the frigate SHEFFIELD and the cargo ship ATLANTIC CONVEYOR, were struck (and sunk) by AM-39 Exocet missiles launched from Argentinian Super Etendard aircraft. The aircraft and missiles had been obtained from France in 1981. [Ref. 9:p. 135]

In 1987, the USS STARK, a frigate, was struck by two Exocets launched from an Iraqi Mirage F-1 fighter-bomber. 37 U.S. sailors were killed and the ship was severely damaged by the missile hits and resultant fires. [Ref. 10:p. 24]

as the one at Dhahran. The ability of U.S. military forces ashore or afloat to protect themselves against such attacks is still quite limited.

In view of the possibilities described above, the U.S. intelligence community must direct its assets and its efforts to provide sufficient warning about nascent cruise missile capabilities. Procedures should be established so that disparate bits of data concerning such things as arms sales, technology transfers, foreign political decisions and various economic and diplomatic factors may be sorted and evaluated within a logical framework for analysis. In this way, forecasting of the threat posed by cruise missiles (either land-attack or anti-ship) in a particular region can be more specific, more accurate and, especially, more timely than present methods of assessment.

Methods currently used are likely to include the following:

1. The worst-case scenario, in which every potential cruise missile threat is assumed to be based upon state of the art technology (i.e., "If it can be built, it will be built--and by everyone."); or

2. The best-case scenario, in which no threat is assumed beyond that which has been demonstrated or observed (i.e., "If we haven't seen it, then they don't have it.").

These approaches to assessing the degree of proliferation of advanced cruise missiles represent the cautious extremes,

and have a certain intrinsic value as such. Both assumptions, however, have notable shortcomings. The assumption that every lesser developed country with a missile program is capable of conducting the equivalent of a Tomahawk strike will severely, and in most cases unnecessarily, complicate American military actions, particularly with respect to counter-targeting and the establishment of an adequate defensive posture for U.S. forces. The other extreme could easily result in American (or allied) military forces being surprised by a previously unseen capability, with tragic results.

Therefore, I propose the implementation of a methodology by which data can be compiled and then utilized to provide a more realistic assessment and projection of emerging cruise missile programs. Through the use of the techniques of Bayesian analysis (described in Chapter V) it should be possible, over time, to forecast the direction of a particular nation's weapons development and acquisition strategy and to provide on demand an assessment of that nation's progress in fielding advanced cruise missile systems.

In order to demonstrate the manner in which Bayesian analysis may be applied to assessing and forecasting cruise missile programs, it will be necessary first to describe the modern cruise missile in more detail. This description, in Chapter II, will include a brief summary of the development of cruise missiles; a description of the Tomahawk family of missiles, which represent the state of the art for operational

land-attack cruise missiles[6]; and a summary of the cruise missile inventory of the former Soviet Union.[7]

In Chapter III, a number of possible reasons why a developing nation might seek to develop an indigenous production capability for cruise missiles will be presented. In Chapter IV, the critical technologies required to build modern cruise missiles will be summarized.

Chapter V will include a description of the concepts of Bayesian analysis, an example of the kind of database it requires and a listing of specific indicators which relate to cruise missile acquisition and development. Chapter VI will apply Bayesian analysis to an illustrative case study. The conclusion will summarize the thesis and provide some comments on the role of intelligence forecasting in the larger arena of national-level policymaking.

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[6] The Tomahawk Anti-Ship Missile (TASM) also probably represents the state of the art in its category. Unlike the TLAM, however, the TASM has not yet been tested in combat.

[7] Several other countries also produce cruise missiles of varying degrees of sophistication. Among the more advanced are the Israeli Gabriel and its South African and Taiwanese derivatives (the Skorpioen and the Hsiung Feng, respectively), the French ASMP, the Italian/French Otomat and the Japanese ASM-1. Space constraints preclude a system-by-system analysis of these weapons.
The Soviet case warrants special attention because of the sheer size of the inventory and the potential for massive proliferation. [Source: The World's Missile Systems, 8th ed., General Dynamics Corp., 1988]

II THE CRUISE MISSILE

A. HISTORICAL DEVELOPMENTS

The concept of a cruise missile, or "flying bomb" has been discussed since the invention of the airplane. Yet most early attempts to build such a weapon were stymied by technological limitations, most notably the inadequacy of early automatic guidance systems. Ironically, during World War I the most promising system for steering an unmanned, bomb-laden airplane into a specific military target was the use of radio controls located in an accompanying manned aircraft, [Ref. 8:pp. 7-40] a method which offered little advantage over the use of manned bombers.

1. The V-1

The first truly operable cruise missile was the German V-1 "buzz-bomb," which was put into service during World War II. It is "now generally accepted as the progenitor of all cruise weapons." [Ref. 12:p. 3] The V-1 was propelled by a pulse-jet engine at speeds up to 650 kilometers (390 miles) per hour and was guided by a pre-set magnetic compass. Targeting was crude: the 900 kilogram conventional warhead detonated on impact, which occurred soon after fuel exhaustion had resulted in engine shutdown. [Ref. 12:pp. 3-4]

Approximately 8,000 V-1s were launched by Germany, primarily against London, and over 17,000 people were killed

by them. Eventually, though, the V-1 was defeated by a coordinated defense composed of early-warning radar stations, anti-aircraft artillery (AAA) batteries and pre-positioned airborne interceptor aircraft. These defensive systems, working in concert, were able to shoot down 95 percent of the later V-1 cruise weapons launched. [Ref. 12:pp. 3-4]

2. Early American Cruise Missiles

Before the end of the war, the United States had developed, but not deployed, its own cruise weapon, the JB-2 Loon. The Loon was essentially nothing more than an American version of the V-1. In 1946, design work began on a new U.S. ground-launched cruise missile, the SM-62 Snark. Powered by a turbojet and carrying a stellar inertial guidance system, in 1959 it became America's first operational intercontinental missile system. The Snark was armed with a four megaton (MT) thermonuclear warhead. A planned follow-on cruise missile, the Navajo, used a ramjet engine to achieve Mach 3 cruising speed while employing a wholly inertial guidance system. Navajo was canceled in July, 1957 as a result of the competing demands of the intercontinental ballistic missile (ICBM) development program. [Ref. 3:pp. 15-18]

In 1954, the Air Force deployed to Europe its first operational guided missile, the TM-61 Matador. The Matador was a mobile, ground-launched, rocket-boosted and jet engine-propelled medium range missile. Although Matador had the potential to carry conventional or chemical warheads, its

primary purpose, along with the Army's Corporal missile and Honest John artillery rocket, was to provide a tactical nuclear capability to North Atlantic Treaty Organization (NATO) ground forces. It had a theoretical range of 1,000 kilometers, but that range was severely reduced by the missile's command guidance system, which required continuous radar tracking from the launch site. [Ref. 3:pp. 21-22]

A second tactical nuclear weapon-bearing cruise missile, the TM-76 Mace, was deployed to Europe in 1959 and subsequently to Taiwan and South Korea as well. The Mace A version used a new guidance system known as automatic terrain recognition and navigation, or ATRAN:

> ATRAN consisted of a search radar, a map-matching device and a terrain clearance controller. During flight, the map-matching device compared the images provided by the search radar with a radar photograph of the terrain overflown that was inserted prior to launch. Errors between the two images were broken down into longitudinal and lateral components and the missile's course adjusted accordingly. [Ref. 3:pp. 22-23]

The Mace A, with ATRAN, had an effective range, using a high-low approach, of about 1,200 kilometers. An all-inertial guidance, high-altitude version, the Mace B, had a range of about 2,200 kilometers. [Ref. 3:pp. 22-23]

The U.S. Navy's first operational cruise missile was the SSM-8A Regulus I, in service from 1955 until 1966. "Regulus I carried a nuclear warhead at high subsonic speed to a maximum range of 440 nautical miles." [Ref. 3:p. 20] It was powered by a turbojet engine and normally would be stored on the deck of a submarine until readied for launch (while

surfaced). It was also sometimes carried aboard cruisers and aircraft carriers. A successor missile, the XSSM-9 Regulus II, was to have had over twice the range of Regulus I and a speed of Mach 2, but it was canceled as the Polaris submarine-launched ballistic missile (SLBM) neared operational status. [Ref.3:p. 20]

From 1960 until 1976 the U.S. Air Force deployed the AGM-28A/B Hound Dog air-to-surface cruise missile, two of which could be carried by a B-52 strategic bomber [Ref. 3:pp. 18-19]. The Hound Dog weighed 4,500 kilograms and carried a one MT nuclear warhead. Its turbojet was capable of sustaining low level flight at a speed of Mach 1.6 for a range of up to 800 kilometers. The weapon had a CEP[1] of about 1.5 km. [Ref. 12:p. 6]

As suggested in Chapter I, cruise missiles began to fall from favor in the late 1950s and beyond, at least among American military leaders (both in and out of uniform). Technological advances in other weapon systems apparently had rendered them obsolete. By 1970 the cruise missile had been virtually abandoned as a potential U.S. strategic weapon system. From that time until now, however, a complex interplay of technological, strategic and diplomatic factors conjoined to bring about the situation which exists today. Such factors include the development of small, efficient

[1] Circular Error Probable: the radius of a circle, centered on the target, within which one half of all shots aimed at that target are expected to fall.

turbofan engines and highly accurate guidance systems; the changing capabilities and vulnerabilities of other U.S. strategic systems; and the signing of a number of arms control accords which, among other things, attached greater relative value to cruise missiles and other non-traditional means of nuclear weapons delivery by imposing limits on the traditional methods (i.e., bombers, ICBMs, SLBMs). [Ref. 3:pp. 28-59, 186-192;Ref. 12:pp. 20-28]

The United States currently possesses two long-range, land-attack cruise missile systems: the AGM-86 air-launched cruise missile, or ALCM; and the BGM-109 Tomahawk sea-launched cruise missile, or SLCM. Both of these systems were originally conceived as delivery vehicles for nuclear warheads.[2] Ironically, while the nuclear variants have been "stood down" and are not deployed presently, conventional versions of **both** the AGM-86 ALCM and the BGM-109 Tomahawk were launched against targets in Iraq during DESERT STORM.[3]

While the AGM-86 ALCM and the BGM-109 SLCM both are examples of extremely sophisticated operational cruise missiles, the Tomahawk is the more publicized of the two.

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[2] In much of the literature on strategic cruise missiles and arms control, the terms SLCM and ALCM are used, without modification, to refer specifically to the nuclear-armed variants of each of these weapon systems.

[3] In January, 1992 the U.S. Air Force revealed that it had launched 35 non-nuclear AGM-86C missiles from seven B-52G bombers. The existence of the conventional variant of the AGM-86 had been classified until the time of that announcement. [Ref. 13:p. 105]

Therefore, it has been selected to demonstrate the existing state of the art in cruise missile technology and performance.

B. THE TOMAHAWK CRUISE MISSILE

The name "Tomahawk" refers to an entire family of sea-launched cruise missiles: a nuclear-armed land-attack variant (BGM-109A or TLAM-N), a conventionally-armed anti-ship missile (BGM-109B/TASM), a conventional land-attack variant with a unitary high explosive warhead (BGM-109C/TLAM-C), and another land-attack variant which carries combined-effect packages of submunitions (BGM-109D/TLAM-D) [Ref. 14:p. 332;Ref. 1:p. 47]. Tomahawk also provided the basis for the Ground-Launched Cruise Missile (BGM-109G/GLCM), a theater nuclear weapon first deployed to Europe in December, 1983 [Ref. 8:pp. 186, 201-205], and subsequently withdrawn. Modified Tomahawks have also been designed for air launch from such platforms as the Navy's A-6E attack aircraft and the Air Force's B-52 strategic bomber [Ref. 8:pp. 207-8].

1. Airframe

All of the Tomahawk SLCMs are built around a common airframe. The missile is powered by a Williams Co. F-107-WR-101 turbofan engine which weighs 275 kilograms and generates 600 pounds of thrust. [Ref. 12:pp. 8-12] This engine enables the Tomahawk to cruise at speeds between 0.5 and 0.75 Mach (380-575 mph or 340-510 knots) [Ref. 15] at altitudes between

100 and 300 feet above local ground level [Ref. 1:p. 47].[4] Other common airframe components include the deployable air injection scoop and folding wings, and the rocket booster which propels the missile to cruise velocity upon launch. The Tomahawk missile, with booster, is 20.5 feet long and has a 21 inch diameter. With wings deployed, the airframe has a span of 8.6 feet [Ref. 15].

2. Guidance

All variants of the Tomahawk have an inertial guidance system which uses accelerometer inputs to update continuously an initial position input prior to launch. Because "the best currently-used inertial guidance systems tend to 'wander' up to 900 meters off course for every hour of flight time" [Ref. 12:p. 12], all the land attack variants are equipped with a terrain contour matching (TERCOM) system which provides periodic positional updates to the inertial system. TERCOM was patented in 1958 by LTV-Electro Systems Company for use in the SLAM (Supersonic Low Altitude Missile) strategic attack missile. Although the SLAM system was canceled, development of TERCOM was carried forward. Ultimately, TERCOM was adopted for use in both the ALCM and the SLCM/GLCM. [Ref. 8:p. 136]

[4] The speed of sound at sea level is 343 meters per second (in dry air, at 20 degrees Celsius and one atmosphere of pressure). There are 1760 yards in a statute mile and 2000 yards in a nautical mile. One meter = 3.28 feet. [Source: Halliday and Resnick, Fundamentals of Physics, 3rd ed., New York, 1988.]

The principles of operation of the combined TERCOM and inertial navigation system, sometimes known as TAINS,[5] are elucidated in Kenneth Werrell's The Evolution of the Cruise Missile:

> In the TERCOM system, engineers divide a terrain map into a matrix of cells which have ranged in size from 100 feet to 3,200 feet on a side....The E-Systems matrix consists of 64 cells, each 400-feet on a side, yielding a 4.9 nm strip map. Engineers assign each cell an average elevation derived from a contour map or satellite reconnaissance map, and this information is stored in the system's computer. In flight, a radar altimeter measures the actual elevations and then at checkpoints matches that sequence with a digital map stored in the computer....
>
> The inertial guidance system navigates the missile to the first TERCOM checkpoint and between subsequent checkpoints en route to the target. At each checkpoint, the computer updates the inertial guidance system and corrects the missile's course. Theoretical accuracy of TERCOM is 0.4 times the size of the cells, which are progressively reduced in size the closer the map set is to the target. [Ref. 8:p. 136]

For the accurate delivery of the W-80 nuclear warhead aboard the BGM-109A, the inertial system with TERCOM updates is adequate. In order for a conventional cruise missile to accomplish its mission, though, a much more accurate terminal guidance system is required. The system incorporated into the BGM-109C and BGM-109D (TLAM-C and TLAM-D) is known as Digital Scene-Matching Area Correlator, or DSMAC. The DSMAC system uses an optical camera to detect images of the ground at prescribed points along the missile's planned flight path to the target. These images are digitized and compared to images stored in the guidance computer's

[5] TAINS: TERCOM-Aided Inertial System

memory. Offsets from the desired path are calculated and a correcting course is determined. [Ref. 2:pp. 72-73]

The range and accuracy attainable by a Tomahawk land-attack missile using TERCOM and DSMAC has been characterized as follows: if launched from the vicinity of St. Louis, Missouri, a TLAM equipped with TERCOM alone could fly to Washington, D.C., and hit a target the size of JFK Stadium. If fitted with DSMAC as well, the missile could be flown through the goalposts at either end of the football field inside. [Ref. 16:p. 4]

The BGM-109B anti-ship variant uses an entirely different guidance system. Since it is employed against ships maneuvering at sea, TERCOM and DSMAC would be useless. Therefore, the TASM is equipped with an active radar seeker (a modified version of the kind installed on the shorter-range Harpoon anti-ship cruise missile). It flies a pre-programmed route to the expected target area, at which time the radar is activated and a search for targets is commenced. [Ref. 14:pp. 332]

3. Warhead

As mentioned above, the TLAM-N is armed with a W-80 nuclear warhead, which at least one reference credits with a 200 kiloton yield [Ref. 12:pp. 14-19]. Both the TLAM-C and the TASM carry a unitary WDU-25/B (Bullpup) 1000 pound high explosive warhead for use against high-value point targets. The TLAM-D, on the other hand, carries up to 24 separately

dispersed packages of submunitions, up to 166 3.4 pound bomblets in all. [Ref. 17:p. 38] These bomblets may be armor-piercing, fragmentation or incendiary [Ref. 1:p. 47], and are likely to be used against concentrations of small, vulnerable high-value targets, such as revetted aircraft or stationary tanks.

4. Launch Platforms

Having described the common airframe of the Tomahawk cruise missile, its various guidance schemes and payloads, we turn our attention to the launch platforms. Tomahawk sea-launched cruise missiles can be launched from a vertical launching system (VLS), a deck-mounted armored box launcher (ABL) or a submarine's torpedo tube. In fact, two of the physical limitations on the size of the missile--its length and its diameter when stowed--were dictated by the operational requirement that it be capable of storage in, and launch from, a submarine torpedo tube [Ref. 3:p. 32]. Specific classes of U.S. naval vessels which were to be configured for Tomahawk include the following: all Sturgeon (SSN-637) and Los Angeles (SSN-688) class nuclear submarines, including some VLS-equipped 688s; all Spruance (DD-963) and Arleigh Burke (DDG-51) class destroyers (VLS); all VLS-equipped Ticonderoga (CG-47) class cruisers (i.e., CG-52 and above); several nuclear

cruisers (ABLs); and the four Iowa (BB-61) class battleships with a staggering 32 ABL "tubes" apiece.[6] [Ref. 18:pp. 486-7]

In conjunction with the large number and variety of launch platforms, procurement of a sizable inventory of missiles is planned. Prior to Operation DESERT STORM, the U.S. Navy had been building toward a total of 4,030 Tomahawks of all varieties by the end of fiscal year 1994 (i.e., by September 30, 1994)[7] [Ref. 15]. While almost 300 conventional TLAMs were expended during DESERT STORM, it is reasonable to surmise that the total Tomahawk inventory is approaching its previously planned level.

C. SOVIET CRUISE MISSILES

In terms of weapon system capabilities, Tomahawk represents the greatest potential danger posed by cruise missiles and by the transfer of cruise missile technology. This is especially true for land-attack missiles. With respect to existing cruise missile inventories and the likelihood of their proliferation, though, the most serious threat to the security of U.S. military forces resides in the stockpiles of the former Soviet Union.

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[6] The Iowa class battleships, all of which were fitted with ABLs, have been decommissioned. Two of them--Wisconsin and Missouri--launched TLAMs against Iraq during DESERT STORM [Ref. :pp. 20-21].

[7] To include 758 TLAM-N, 593 TASM, 1,493 TLAM-C, and 1,186 TLAM-D

The Soviet Union has been building and deploying air- and sea-launched anti-ship cruise missiles since 1958 and 1960 respectively. While almost always lagging behind U.S. technological capabilities, the size, speed and range of these weapons have long posed a serious hazard to U.S. naval forces. Much of the U.S. Navy's tactical doctrine, in fact, has been designed to counter the threat of attack by these weapons. The Aegis weapon system, likewise, was designed explicitly to prevent saturation of U.S. aircraft carrier battle group defenses by Soviet cruise missiles.

The disintegration of the Soviet Union, with its resultant political upheaval, economic turmoil, and eruption of ethnic and national rivalries, raises the frightening prospect of a virtual free market in arms trading. The government of the Commonwealth of Independent States (CIS) has been largely unsuccessful in converting military production facilities to domestic applications. Government-sanctioned exports of existing weapons inventories (including, for example, high-performance aircraft such as the MiG-29 "Fulcrum" and Su-27 "Flanker" [Ref. 19:p. 430]) are viewed increasingly and accurately as a major source of much-needed foreign hard currency. [Ref. 20:pp. 253-4] Furthermore, "[t]he decay in the functional unity and morale of the former Soviet military raises the question of the fate of its conventional weapons and the prospect of their proliferation

among local **warlords, criminals and terrorists**." [Ref. 21:p. 231; emphasis added]

Most reports of arms sale proposals and of attempts to acquire weapon system stockpiles by force have involved more conventional weapons, such as tanks and aircraft. The same economic and political forces also apply, though, to the proliferation of "unconventional" weapons, including nuclear, chemical and biological warheads, ballistic missiles and, of course, cruise missiles. Therefore, prudence dictates that any assessment of the threat posed by cruise missile proliferation should include an accounting of the existing inventory of Soviet cruise missiles.

Like the United States, the Soviet Union recognized the cruise missile's potential as a nuclear weapon delivery vehicle. The Soviets, however, placed much more emphasis on the missile's tactical applications, particularly at sea. Furthermore, the Soviets did not shelve cruise missiles once they fielded ICBMs and SLBMs. Rather, they continued to develop anti-ship cruise missiles--both air- and sea-launched versions--primarily for use against U.S. Navy surface ship battle groups. Air-launched cruise missiles deployed for this purpose include the AS-4 Kitchen (1967), the AS-5 Kelt (1968) and the AS-6 Kingfish (1968). Comparable sea-launched cruise missiles are the SS-N-7 Starbright (1968), SS-N-9 Siren (1969) and the SS-N-12 Sandbox (1976). [Ref. 5:p. 156]

In 1980 the Soviet Union deployed a new generation of sea-launched cruise missiles: the SS-N-19 Shipwreck and the SS-N-22 Sunburn. "While these missiles offered significantly improved anti-ship capabilities, they [were] primarily modern versions of a long line of relatively short-range weapons designed for surface ship attacks." [Ref. 5:p. 156] Shortly thereafter, though, development began on "a new generation of long-range, nuclear-armed, air-, sea-, and ground-launched, land-attack cruise missiles...similar to current U.S. long-range missiles." [Ref. 5:p. 156] These include the AS-15 Kent and the SS-N-21 Sampson, which both now have been deployed, as well as the SSC-X-4 ground-launched cruise missile, the deployment of which was suspended by the Intermediate-Range Nuclear Forces (INF) treaty [Ref. 5:p. 156].

The Natural Resources Defense Council, Inc., in its 1989 Nuclear Weapons Databook, attempted an assessment of the total number of Soviet cruise missiles deployed, by type. Estimates for each type of sea-launched cruise missile were obtained by counting the number of launch platforms (i.e., ships and submarines) and assuming that one missile exists for each launcher.[8] This methodology assumes, of course, that there are neither significant shortages nor stockpiles of cruise missiles. Its accuracy depends, therefore, on the validity of those twin assumptions.

[8] For example, if a Charlie I class submarine can carry eight SS-N-7s, and there are nine Charlie I subs [Ref. 22:p. 131], then there are probably around 72 SS-N-7s in the Soviet inventory.

Applying the above-described methodology but using more current order of battle data from the International Institute of Studies (The Military Balance 1991), an estimate of the Soviet sea-launched cruise missile inventory at the time of the August 1991 coup can be compiled. Particularly noteworthy are the resulting estimates of around 250 SS-N-19 Shipwreck ASCMs, which have a range of 550 kilometers; up to 80 SS-N-21 Sampson land-attack cruise missiles (3000 kilometer range); and a total inventory of over 1100 sea-launched cruise missiles.

Further evidence of a substantial inventory of modern sea-launched cruise missiles is the completion in 1991 of another SS-N-19-capable Oscar II SSGN, along with an Akula and a Victor III SSN, both of which can carry SS-N-21s [Ref. 6:p. 348]. Moreover, the Russian Federation alone is assessed to have some 84 ALCM-equipped TU-95M "Bear" bombers [Ref. 23:p. 14], whereas in 1989 "an inventory of some thousands of ASMs [were] estimated to exist, armed with 2000 nuclear warheads." [Ref. 5:p. 157]

The economic incentives for elements of the former Soviet Union to sell off some of this inventory are clear. So too are the motivations for newly unemployed Soviet weapons designers to market their expertise around the world. On the other side of the equation--the arms and technology buyers--the agendas are not so simple. There are many reasons why a developing nation might choose to buy advanced cruise missiles

or to acquire the capability to build them. Their tactical value in time of war is only one such reason, and probably not the most important one.

III MOTIVATIONS FOR CRUISE MISSILE PROLIFERATION

Seth Carus, a previously-cited expert on missile proliferation, has identified three reasons why a country might seek to acquire a ballistic missile inventory. His reasons included "strategic status" "strategic deterrence," and "military value" [Ref. 4:pp. 3-11]. Dr. Scott Tollefson, a professor of Latin American studies at the Naval Postgraduate School in Monterey, explained Brazil's pursuit of an indigenous *ballistic* missile production capability in similar terms. He described "political," "economic," "security" and "technological" factors which influenced the Brazilian government's course of action. [Ref. 24:pp. 21-27]

With the development of accurate, long-range land-attack cruise missiles, the same factors which influence ballistic missile acquisition and development can be applied equally well to cruise missiles. This is especially true for missiles which have been, or can be, mated with nuclear, chemical or other unconventional warheads.

Following the lead of Carus and Tollefson, there are at least four reasons why a developing nation might choose to pursue the capability to produce cruise missile indigenously. These reasons include increasing the nation's international status or prestige, serving as a vehicle for accelerated

industrialization, filling a specific military need, and giving the nation some form of economic benefit.

A. INTERNATIONAL PRESTIGE

For over forty-five years, nuclear weapons have been a *sine qua non* of superpower status. The ballistic missile, as a primary nuclear weapon delivery vehicle, has shared in "the bomb's" sense of prestige. In South America, for example, "devoid of major external conflicts, the prestige rationale drives much of the arms transfers within the region **and the missile programs in Argentina and Brazil**." [Ref. 24:p. 22; emphasis added] A nuclear-capable cruise missile production capability would command as much respect from allies, neighbors and regional competitors as do today's indigenous ballistic missile programs (such as Israel's Jericho missile system).

Even without a known or suspected nuclear weapon capability, a country's possession and, especially, its production of advanced cruise missiles is sure to be noticed. Again drawing an analogy to ballistic missiles, the possession by Iraq of SCUD missiles (and its ability to modify them) weighed heavily on the diplomatic and, to a lesser extent, the military preparations of the United Nations coalition forces prior to the 1991 Persian Gulf War. Only after the war began, and the inaccuracies of the Iraqi SCUD became apparent, did concern over the SCUD diminish.

Had the Iraqis been using modern cruise missiles instead, with precision guidance systems, low visibility flight paths and tiny radar cross-sections, their impact on the conflict would have been much greater. Against a more evenly matched foe, the effect of cruise missiles could have proven decisive. The recognition of that possibility, by the leaders of regional military powers, will serve to attach to cruise missile possession and production the same prestige now associated with ballistic missiles and, by extension, nuclear weapons.

B. ACCELERATED INDUSTRIALIZATION

Many of the world's lesser developed countries (LDCs) look to the Western industrialized nations with a sense of longing, if not outright envy. The leaders of these LDCs contrast the relative affluence of Western Europe, Japan and the United States with their nations' poverty and resultant instability--and they seek change. As of 1990, "more than 100 countries [were] committed to programs of economic development intended to break the vicious cycle of poverty." Their way out, their "supreme national goal," was industrialization. [Ref. 25:p. 518]

In 1978 the economist E. Benoit published a study which indicated that, contrary to expectations, increases in defense spending in LDCs "ha[d] a **positive** effect on the rate of growth of material product (income)." [Ref. 26:p. 214] Benoit attributed the economic benefits of defense spending to such

things as the care and feeding of the troops, higher standards of education and medical care, improvements made to the nation's infrastructure in the name of national security, and subsidization by the military of otherwise useful scientific and technical research and development. [Ref. 26:p. 215]

Others have seen investment in high-technology defense-related industries as the way out of poverty and into the First World. "To become mature economies, the developing nations must undertake a massive transformation of their societies....To succeed...they need the capital goods and technology of the developed, industrial countries." [Ref. 25:p. 523] The fastest way to obtain such capital goods and technology, many LDC leaders seem to believe, is to develop the capability to produce indigenously, often under a licensing or co-production agreement, the same military hardware used by the industrialized countries. [Ref. 27:p. 4]

Iran was one of the first LDCs to embark on such a program, commencing in 1970. Shah Reza Mohammad Pahlavi's Import Substitution Industrialization (ISI) program "involved an unprecedented, large-scale transfer of technology by some of the West's biggest defence conglomerates to a Third World state." [Ref. 28:pp. 158-9] Such technology transfers to Third World licensed arms producers have now become commonplace; the willingness to provide such transfers is in many cases a prerequisite for doing business [Ref. 29:p. 72].

Cruise missiles would appear to be an ideal weapon system, the production of which could lead to industrial and technological advances in the civilian sector of an LDCs economy. Agreements with developed nations could range from final assembly work, to manufacturing of airframe and propulsion subsystems, to indigenous production of complex microelectronic guidance circuitry. The knowledge, skills and industrial capacities needed to build cruise missiles could then be channeled into both missile production for host-nation use and civilian applications.

C. MILITARY NEEDS

As was already noted, possession of cruise missiles could give a nation (or at least its leaders) an enhanced sense of international prestige or status. While such prestige is itself a reason why a nation might choose to pursue a cruise missile development and/or acquisition program, there is a more fundamental reason for such a course of action. Quite simply, cruise missiles are a powerful military instrument.

Many nations already possess some form of cruise or prolonged glide weapon. The ubiquitous Styx missile, a two-and-a-half ton, turbojet propelled anti-ship missile with a 400 to 500 kg high explosive warhead and either active radar or infrared (IR) homing (depending on the variant), has been

in service since 1958.[1] As of 1988, it was being used by at least 22 nations for coastal defense missions. The worldwide inventory of Styx missiles numbers in the thousands. [Ref. 14:p. 318]

Likewise, the French-made Exocet[2]--a ground-, air-, surface-, and submarine-launched family of rocket propelled, sea-skimming, active radar homing anti-ship missiles--has been sold to no less than 24 other countries around the world [Ref. 14:p. 66]. It has been proven in combat to be a highly effective weapon.

The Tomahawk, of course, has validated the concept of a conventionally-armed, precision-guided, land-attack cruise missile. Consequently, there are dozens of nations which might reasonably conclude that an advanced cruise missile--either a land-attack version, an anti-ship version, or both--is a valid military requirement. Likely candidates for the anti-ship version are those countries which now deploy the Styx, the Exocet, the U.S. Harpoon, the Italian/French Otomat, or any derivative of the Israeli Gabriel anti-ship missile.

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[1] The dates of Initial Operational Capability (IOC) for each variant are as follows: SS-N-2a--1958; SS-N-2b--1964; SS-N-2c--1967. [Ref. 14:p. 318]

[2] There are at least four variants of the Exocet.

1. MM38: IOC 1974, 42 km maximum range, original ship-launched missile.
2. AM39: IOC 1976, 50-70 km max. range, air-launched variant.
3. SM39: IOC 1986
4. MM40: IOC 1981, 70 km max. range, extended-range version of MM38; ship- or truck-launched capability (for coastal defense). [Ref. 14:pp. 66-68]

Other candidate nations for new anti-ship cruise missile programs are those countries involved in any sort of sea control dispute (e.g., possession of the Spratly Islands, which are claimed by China, Vietnam, the Phillippines, Malaysia, Indonesia and Brunei).

Countries which might see a legitimate military requirement for an advanced land-attack cruise missile program include those which have active ballistic missile development programs or other strategic strike programs (e.g., Brazil, China, Taiwan), or countries involved in regional arms races or border disputes (e.g., Argentina, Chile and Peru [Ref. 30:p. 228]; India and Pakistan).

Finally, any country which previously has purchased (or been given) anti-ship or deep land-attack weaponry from either the United States or the former Soviet Union may be embarked already on a program to produce cruise missiles indigenously in an effort "to reduce their dependency on a single supplier...and thereby to avoid any supplier-imposed conditions that might curtail their freedom of political and military action." [Ref. 27:p. 4]

D. ECONOMIC BENEFITS

The international arms trade can be a lucrative business. Marketing of the right weapon system, at the right time, can prove to be very rewarding financially for the manufacturer of that weapon, and for the manufacturer's host nation. Indigenous arms production offers additional economic benefits

to a national government which previously had to import military hardware from abroad: conservation of foreign currency and a more positive balance of trade.

One of the biggest disadvantages of indigenous production often is the inability to achieve economies of scale. Even for large Western industrialized nations (such as France), producing weapons for domestic requirements alone would be terribly inefficient. This is why France, West Germany and other advanced nations (including, in many cases, the United States) are quite willing to market their most advanced weapon systems to anyone who can afford them. [Ref. 27:p. 6]

For small LDCs, the situation is problematic: foreign purchases lead to balance of payments problems or depletion of currency reserves, along with a degree of depende‹ e; indigenous production is inefficient and diverts much-needed capital, resources and skilled labor from other pressing domestic needs. [Ref. 31:p. 329]

Nevertheless, a nation able to secure a niche in the international arms transfer market may be able to overcome the negative aspects of domestic production. In 1989,

> at least 120 countries participated in the arms trade....All 120 were importers, and 47 of them also exported. Ninety-three of those participating in the trade were less developed countries, and they accounted for three-quarters of all arms imports and one-tenth of arms exports, by value.... International transactions in arms...accounted for about [1.5] percent of world trade in 1989. [Ref. 32:p. 47]

For the country first able to field and market a highly desirable product (such as the Exocet), there may be much

money to be made from international sales. That prospect could provide a powerful incentive to the leaders of some developing country rich with idled skilled workers but suffering from moderate balance of payments problems.[3]

One example of a country attempting to do exactly that is North Korea, which in 1989 was trying to develop an indigenous production capability for the Chinese HY-2 "Silkworm" anti-ship missile. The goal of such production was to offer the missile "for possible sale to such countries as Iran." [Ref. 33:pp. 204-207]

E. CONCLUSIONS

It is impossible to predict with any certainty, based only on the broad motivations sketched out above, precisely which countries, if any, will decide to acquire advanced cruise missile systems or attempt to build such systems indigenously. It *is* possible, however, to evaluate a country's physical capability to do so, by considering their

> technological base, necessary production experience, and required engineers and technical management teams to produce most [weapon] systems as redesigned copies, or with increased use of domestic or foreign components. [Ref. 27:p. 8]

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[3] Looney and Fredericksen, Ref. 31, argue that for countries that are not constrained by their international borrowing capacity, there is no negative correlation between increased defense spending and economic growth (i.e., growth will not be hindered by increased defense spending). Countries which are resource constrained, on the other hand, (i.e., a troublesome level of foreign debt), will be significantly negatively affected by increases in defense spending.

The Science Applications International Corporation did so, and grouped developing nations into four "tiers" of potential "new suppliers" of arms [Ref. 27:p. 8]. Only the first tier would "be capable of relatively autonomous production of a wide range of military equipment," while the second tier would be capable of a "comparable level of production sophistication, but only for selected types of equipment." [Ref. 27:pp. 8-9] The first and second tiers consisted of six and four countries, respectively [Ref. 27:pp. 8-9].[4] Therefore, by focusing attention on the few countries likely to be capable of cruise missile production and looking for evidence of action on any of the motivating factors described herein, it should be possible to identify nascent missile production programs in their earliest stages.

[4] First tier countries included China, Brazil, Israel, India, South Korea and Yugoslavia. Second tier countries included Argentina, Taiwan, North Korea and Egypt. [Ref. 27:pp. 8-9]

IV CRUISE MISSILE CRITICAL TECHNOLOGIES

Once it has been determined, or even suggested, that a particular nation has decided to embark on a cruise missile acquisition and/or indigenous production program, the next logical step is to analyze the direction which the program is taking. An assessment should be made of the intended nature of the missile system: its mission, characteristics and capabilities. A judgment can then be offered, and over time revised, of the subject nation's ability to meet its goals in building a modern cruise missile.

Any cruise missile system can be evaluated on its capabilities in a number of specific characteristics or categories. The results of these evaluations, individually and holistically, define the technological sophistication of the weapon system and provide a suggestion of the threat posed by it.[1] In general terms, a modern cruise missile system is one which is capable of delivering its payload, reliably and accurately, to a target at long range. Implicit in the term reliability is the concept of survivability: not only must the missile be substantially free from electro-mechanical

[1] The actual threat posed by any given weapon system is a function of many variables, including, for example, the system's theoretical capabilities, the training and morale of its operators, the quality of leadership exercised, and the logistical support available. This list is merely suggestive, not comprehensive.

failure; but it also must be capable of penetrating, with high probability, a robust active defensive system.

There are three fundamental categories of technological capability which are essential to the construction of a modern cruise missile system. The three categories are airframe and propulsion, guidance, and warhead technology. A fourth category, overlapping and intertwined with the first three, is low-observable, or stealth, technology. Additional capabilities not integral to the missile itself are also required if the development program is to be successful. Technical and operational test and evaluation facilities are an excellent example of such capabilities.

Because of the omnipresent nature of stealth technology--the need to consider observability in almost every aspect of missile design--it is to this topic we first turn our attention.

A. STEALTH

Any weapon system, no matter how sophisticated, is worthless if it cannot put ordnance on target a sufficient percentage of the time. Strategic land-attack systems often face a daunting array of defensive measures, ranging from early warning to detection and tracking to soft or hard kill of the delivery vehicle. Consequently, each strategic system is endowed with certain characteristics which enhance its survivability. ICBMs fly too high and too fast, and approach at too steep an angle, to be threatened seriously by shootdown

(so far). [Ref. 4:p. 10] Their time of flight allows minimal reaction time, and they can complicate tracking by releasing decoys. Manned strategic bombers fly very low and very fast, and have the further advantage of man-in-the-loop control. They also undoubtedly possess very sophisticated electronic countermeasures (ECM) gear for self-defense, and some are able to "shoot their way in," so to speak, through the use of air-launched missiles targeted at specific air defense sites.

Cruise missiles, whether land-attack or anti-ship, have few of the advantages of either ICBMs or manned bombers. They travel at sub-sonic speeds, along pre-determined flight paths, and have no self-defense capabilities. A cruise missile's survival depends almost entirely upon its total avoidance of detection throughout its ingress to the target.

There are two principal ways by which a cruise missile can be detected and tracked by an air defense system. The first is by reflection of electromagnetic (EM) energy, i.e., radar, off of the target. Radar detection depends upon the radar cross section (RCS) of the missile and its entry within line-of-sight (LOS) distance from the search radar antenna.[2]

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[2] Radar detection of a target depends upon a large number of factors, including transmitted power, range to the target, radar receiver sensitivity, operator training and alertness, antenna size and characteristics of the transmitted radar pulse. Most of these parameters are beyond the control of a cruise missile designer.

Radar cross section is a nominal value ascribed to a particular airframe. It is used primarily as a tool for comparison with other airframes. Actual RCS of a given target to a given radar fluctuates wildly with target aspect (i.e., nose-on, look-down or beam reach.

The other way in which a cruise missile readily may be detected is by its emission of thermal infrared (IR) EM energy. Such detection depends primarily upon the temperature of the missile (more accurately, its exhaust) relative to its surroundings. Cruise missile designers, therefore, try to reduce the probability of detection by minimizing the missile's radar cross section and IR signature, while mission planners attempt to avoid flying the missile within line-of-sight distance of any radars. These goals are accomplished through miniaturization, stealth construction, flight path design, and engine design.

1. Miniaturization

Radar cross section is determined roughly by the surface area of radar-reflective material oriented toward the radar antenna. Any action to reduce the size of the cruise missile generally will reduce the missile's RCS. It was a fortuitous series of "technological developments in propulsion units, guidance systems, and warhead design" [Ref. 3:p. 6] that allowed construction of a small cruise missile by the United States.[3] Further miniaturization of missile components and subsystems remains a fruitful means of increasing survivability of newly designed cruise missiles.

[3] By 1970, the guidance package for U.S. cruise missiles being considered for development was only one and one-third cubic feet in size and weighed 115 pounds [Ref. 8:p. 136].

2. Stealth Construction

Besides decreasing the physical size of the missile, there are at least two other ways to reduce its RCS. The first is to construct the missile body of composite materials which are more absorptive, and therefore less reflective, of EM energy. The same affect can be achieved through the application of a coating of highly absorptive material--stealth paint, in other words--over more traditional airframe materials.

Radar cross section can also be reduced by constructing the airframe in such a way that EM energy is scattered rather than reflected back toward the search radar antenna. Flat surfaces and the intersections between them provide especially strong return signals, so stealthy construction seeks to replace such features with curves and multifaceted surfaces. The result is much more diffusion of the already lower level of reflected (vice absorbed) energy.

A basic cruise missile, with aluminum skin and no stealthy features, will have an RCS on the order of one square meter [Ref. 34:p. 12]. A more advanced design, incorporating radar-absorbing material and "eliminat[ing] retro-reflecting structures," may be capable of achieving a two-orders-of-magnitude reduction; i.e., 0.01 square meter RCS [Ref. 34:p. 14]. In France, a facility has been planned which will measure the RCS of newly designed missile systems. The goal

of this facility is to achieve RCS reductions down below 1/1000 of a square meter (-30 dBm). [Ref. 35:p. 472]

3. Flight Path Design

A search radar's basic detection envelope is a function of two variables: range and altitude.[4] Generally speaking, the lower the altitude at which the object flies, the closer to the radar it must come before it can be detected. The object must be, in effect, above the radar horizon.[5]

A cruise missile's flight path will be designed to keep the missile below the horizon of any known enemy radar sites (in particular, air defense radars). This is equally true for land-attack and advanced anti-ship cruise missiles (e.g., TASM). Evasion may be accomplished through a broad range of altitude and distance combinations.

Not all search radar locations are certain to be known, however. So for added protection, cruise missiles are designed to fly at extremely low altitudes. This characteristic not only makes avoidance of known radar sites easier (by reducing the required stand-off range), but also increases the missile's probability of survival against unknown air defense sites. Probability of detection is

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[4] Antenna height, ground return, terrain features and antenna fade zones also can play a significant role in the shape of the detection envelope.

[5] Because of the propagation characteristics of EM energy near the surface of the Earth, radar horizon is about one-third greater than the visual horizon.

decreased and, should a detection occur, reaction time available to the defensive system will be minimal [Ref. 8:p. 139]. Against targets with terminal defense systems, such as warships, a sea-skimming approach offers the best chance of success.

There are, however, two significant drawbacks to extremely low-altitude flight. First, it is not very fuel-efficient. The maximum range of an air-breathing engine propulsion system varies tremendously with air density, which in turn is a function primarily of altitude. A higher cruise altitude translates into lighter air, which results in greater range for the missile.

Second, extreme low-altitude flight over land imposes the risk of "clobber,": the inadvertant impact of the missile into an uncharted vertical obstruction. For this reason, modern cruise missiles such as TLAM are equipped with a terrain-following system

> consist[ing] of a downward looking radar altimeter (also used by TERCOM) linked to the missile's controls. The planners set a preplanned separation altitude that is a tradeoff between flying very low (making detection and tracking more difficult) and flying at a higher altitude (with less risk of hitting the ground). The addition of a forward looking radar...could further lower these altitudes, but would also add weight, increase complexity, and radiate a signal that defenders could detect. [Ref. 8:p. 139]

Given the premium placed on stealthiness, the installation of a forward-looking active radar on any new land-attack cruise missile seems unlikely. It must be noted, however, that many anti-ship missiles, targeted against fast-moving metallic

structures at sea, depend heavily upon active radars to acquire their targets. Ironically, these anti-ship missiles are much less vulnerable to "clobber" and therefore do not have any need for a terrain-avoidance radar.

4. Engine Design

In addition to detection by radar, cruise missiles can be detected and tracked by the infrared energy generated by their engines. Ballistic missiles and manned aircraft can be detected in similar fashion. The advantage enjoyed by cruise missiles in this venue is one of size: a small turbojet or turbofan engine produces far less heat than an ICBM or large manned bomber.

Efforts to reduce further the IR signature of cruise missiles can be expected to continue. Already, the shift from turbojets--used by the larger, supersonic Soviet designs--to smaller, subsonic turbofans in the U.S. ALCMs and SLCMs have resulted in a decrease in engine exhaust gas temperature from 1,450 degrees Farenheit to 600 degrees Farenheit [Ref. 36:p. 23].

B. AIRFRAME AND PROPULSION

Three basic methods of propulsion have been implemented successfully for cruise missiles: liquid-fuel rockets, conventional jet engines (including turbojets and turbofans), and ramjets [Ref. 34:p. 20]. A primary advantage of the turbine engine designs--increased stealth-- was presented above. The other factors which are likely to determine the

selection of a propulsion system for nascent cruise missiles are the related performance characteristics of range and speed, and the technological sophistication required to construct the various systems.

1. Liquid-fueled Rockets

For short-range applications (less than 100 km), liquid-fueled rockets offer the advantage of simplicity of design relative to the other options. "For longer ranges, however, the size and weight imposed by the need to carry oxidizers, make liquid-propulsion systems infeasible." [Ref. 34:p. 20]

2. Conventional Jet Engines

Turbojets and turbofans, because of their higher fuel efficiency, are capable of achieving much greater ranges than rockets. A developing nation, moreover, would not necessarily require a propulsion system with the technological sophistication of the Tomahawk. A larger conventional jet engine could be used, in which a degree of stealthiness is sacrificed for the sake of lower cost and greater availability. [Ref. 34:p. 20]

> Engines of the size required for cruise missile applications are marketed by numerous sources including India, Israel, Japan [and] Poland....It is also likely that South Korea, Taiwan, Indonesia, Singapore, Spain, and Brazil have the basic technology required to develop and build such engines. [Ref. 34:p. 20]

3. Ramjets

A third propulsion option "for applications where time of flight at long range is a major concern" is the use of

a ramjet engine [Ref. 34:p. 20]. A ramjet is "a jet engine, without moving parts, in which the air for oxidizing the jet fuel is continuously compressed by being rammed into the inlet by the high velocity of the aircraft." [Ref. 37:p. 1175] Several early U.S. cruise missile designs incorporated ramjet propulsion without success (e.g., Navajo, Rigel, Regulus II) [Ref. 8:pp. 98, 100, 117, 131]. The principal advantage of a ramjet is supersonic speed: the ramjet-propelled Russian Kh-31 air-to-surface missile, which debuted at the 1991 Dubai Air Show, allegedly had a cruise speed of almost Mach 4.5, with a range greater than 100 km [Ref. 38:p. 750].

Regardless of the particular propulsion system chosen, the parameters to note include size, weight, thrust and specific fuel consumption (SFC). Size affects stealthiness and launch platform compatibility (e.g., submarine torpedo tube launch). The thrust and weight together determine how large a payload (ordnance, fuel and guidance package) the missile can deliver. Specific fuel consumption--the amount "of fuel...consumed [in pounds] per hour per pound of thrust generated" [Ref. 3:p. 6]--is a measure of engine efficiency which, combined with fuel capacity, determines the missile's theoretical maximum range.

To provide a reference for comparison, the Williams Research Corporation turbofan engine used in the Tomahawk and the ALCM, designated F107-WR-100/101, is only twelve inches in

diameter and weighs 130 pounds. It has an SFC of 0.7 and generates 600 pounds of thrust [Ref. 3:p. 10].

C. GUIDANCE

"Of all the technologies associated with the cruise missile, the most crucial is, and always has been, guidance." [Ref. 8:p. 135] The types of warhead which may be employed effectively, and therefore the missions to which cruise missiles may be assigned, depend primarily on the accuracy of the guidance system(s) installed. Such systems may be divided into three broad categories: initial guidance systems, midcourse update systems, and terminal guidance systems.

1. Initial Guidance Systems

A wide variety of schemes have already been mentioned by which a cruise missile might be guided from the moment of launch. Attempts have been made, with varying degrees of success, to use command guidance (from either a ground radar site or an accompanying manned aircraft); a pre-programmed autopilot or pre-set compass (possibly with stellar updates); or some form of inertial guidance system.

The effectiveness of inertial systems depends upon the accuracy of the input launch position and the target position and upon the drift rate of the system. Even the best inertial systems "drift over time" at a rate of about 750 to 900 meters per hour [Ref. 3:pp. 7-8]. Therefore, inertial systems by themselves are only practical for cruise missiles with nuclear warheads or for land-attack missiles with an area

barrage mission. Even so, the effective range of an all-inertial guided cruise missile is quite limited.

2. Midcourse Updates

It was for precisely that reason that TERCOM was developed. TERCOM, described above in Section II, has been credited in open sources with an accuracy "between 100 and 600 feet, with a 165-foot accuracy supposedly demonstrated in 1960." [Ref. 8:pp. 137-9] The TERCOM system, however, requires an extensive base of geodetic data which may not be readily available to many aspiring cruise missile builders and employers. In any event, there is now a much more cost-effective alternative: the Global Positioning System, or GPS.

GPS is a U.S.-made precision navigation system with both military and civilian applications. The heart of GPS is a constellation of satellites, each of which transmits an encoded signal containing time, position and orbital data. A GPS receiver within view of at least four satellites can determine its own position in three spatial dimensions plus time. Successive readings, fractions of a second apart, enable the receiver to compute its instantaneous velocity [Ref. 36:p. 23].

The accuracy of a GPS receiver depends upon which of the two transmitted signals--Course/Acquisition (C/A) or Precision (P)--it is able to use. The P code is encrypted, and thus is available only to military receivers with proper decryption data. The C/A code is unencrypted and available to

commercial GPS receivers. Such receivers are now readily available and were invaluable to DESERT STORM forces unable to obtain the military version. These receivers, "small enough to fit inside cruise missiles," have an accuracy on the order of 100 meters [Ref. 39:p. 49].

The United States plans to install a GPS capability in the Block III Upgrade to Tomahawk. Supposedly, GPS

> will not improve the missile's terminal navigation accuracy at the target. And it will not expand the types of targets it can successfully engage. It will, however, allow mission routes to be generated over areas where no TERCOM exists. [Ref. 2:p. 74]

Other nations may soon follow suit. At least one integrated GPS/inertial navigation system is already under development in a foreign country, albeit for a manned aircraft. The French company, SAGEM,

> has offered [it] to the French government to equip the Rafale fighter aircraft....
>
> Later this year, SAGEM will deliver a hybrid GPS/INS system using Rafale's ring laser gyro nav/attack system, RL 90, for testing...
>
> The new P(Y) GPS uses an "all-in-view" concept involving the ability to track all satellites in view through up to 12 parallel channels. [Ref. 40:p. 559]

It would be reasonable to assume that what is available in France will soon be available to arms producers worldwide.

The discussion of midcourse guidance systems and GPS would not be complete without at least mentioning one more emerging technology: differential GPS, or DGPS. DGPS is an attempt to further improve the accuracy of a GPS-based position system. It would operate as follows: a GPS receiver

would be installed in a known, fixed position. It would receive the transmitted GPS signals, compute its position based on those signals, and compare that position with its known, true position. A correction factor could then be generated and transmitted. Other GPS receivers within reception range of the master receiver's position could then apply that same correction to their own GPS-calculated positions. In this way, any systemic errors (including deliberately induced ones) could be filtered out.

The manner in which DGPS could be applied to a long-range weapon system such as a cruise missile is not yet clear.

3. Terminal Guidance

The most accurate battle-tested terminal guidance system for land-attack cruise missiles is, of course, DSMAC. Yet, like TERCOM, DSMAC has a number of drawbacks. Primary of these to a developing nation is the requirement for overhead imagery data even more precise than those used by TERCOM. Therefore, other methods are likely to be attempted.

One eminently practical homing system is an active radar. This is the primary means by which most anti-ship missiles acquire their targets. The technology is proven, it is readily available, and it requires minimal targeting information. On the other hand, active radars are not terribly discriminating,[6] they are susceptible to electronic

[6] Lacking very sophisticated data processing, an active radar terminal guidance system tends to home on the largest target, rather than the most desirable.

countermeasures, and they anounce their arrival in an area rather definitively. Also, they are unsuitable for all but the most unusual land-attack missions.

A second, closely related method of terminal guidance is the use of radio frequency (RF) homing. In this method, a radar receiver is mounted in the missile. Rather than transmitting its own signal, the missile homes on its target by detecting and steering toward the target's own radar or radio transmission. Advantages include a more stealthy approach, a degree of target discrimination (varying with the software but much more developed than with active radar), and feasibility for land-attack missions. The principal disadvantage of passive RF homing is obvious: if the target stops transmitting, the missile will lose track on it. [Ref. 34:p. 12]

Passive IR homing is the other method generally available to a nascent cruise missile developer [Ref. 34:p. 12]. It shares many of the advantages and disadvantages of RF homing, although its ability to classify targets is much more uncertain.

D. WARHEAD

1. Relationship Between Warhead and Missile Design

To the battlefield or afloat battle group commander, it is vital to know the nature of the warhead contained in an inbound cruise missile. The difference between a nuclear, chemical, high explosive or other type of cruise missile is a

matter of tremendous tactical significance to both the launching and receiving forces. Beyond that truism, though, the relationship between the warhead and the cruise missile design can be seen in several ways. These ways include determination of the missile's size and weight parameters, guidance system requirements, and the missile's maximum range.

a. Range Requirements

Definition of range requirements is a fairly straightforward process in itself. By matching anticipated launch platforms and launch positions with likely targets, and adjusting for missile maneuverability and safety margins, the required maximum range practically defines itself. This requirement then becomes a small cog which drives many wheels.

b. Warhead Size and Weight

The size and weight of a cruise missile's warhead are constrained on the high end by the capabilities of the propulsion system, the maximum range requirement, and by the degree of stealthiness which the missile's designers wish to achieve. On the low end there are limits as well. A nuclear warhead of a particular yield requires a specific amount of fissile material and shielding. Reducing size and weight beyond the minimum would defeat the purpose of building the missile. Likewise, the range of a cruise missile with a high-explosive warhead could be incrementally increased by replacing a portion of explosive material with extra fuel. At some point, though, there is insufficient explosive energy

remaining for the missile to achieve satisfactory results against its targets. One of a cruise missile designer's functions must be to define the limits of such trade-offs.

C. Airframe Volume

Another important consideration is <u>link between warhead type, desired results, and the accuracy required to achieve those results</u> with the prescribed warhead at the maximum anticipated range. Trade-offs abound. Space within the airframe for precision terminal guidance must be taken from warhead or fuel volume. A bigger warhead means less precision or shorter range. As an alternative, stealthiness may be sacrificed in order to fulfill requirements in any of the other parameters.

How, then, is the selection of warhead type--nuclear, chemical or high-explosive--reflected in a cruise missile's other design choices?

2. Effects of Specific Warhead Types

Perhaps the closest design link is between the warhead and the guidance system. As was indicated above, a small high-explosive warhead like that found in any reasonably stealthy land-attack cruise missile requires pinpoint guidance. Chemical weapons, aimed at small areas (such as troop formations) rather than targeted at points, have more relaxed guidance requirements. Use of nuclear weapons ashore

by a Third World nation would likely be countervalue[7] in nature, and so would have the least restrictive guidance system requirements. Anti-ship cruise missiles will likely be guided as in the past: inertial systems for nuclear-armed ASCMs, with active radar or passive EM or IR homing for more precise conventional attacks.

Another, looser association exists between warhead type and missile range. A chemical weapon, for example, is not likely to be targeted against anything beyond a couple of hundred miles away. The missile's time of flight, and the shifting vulnerability (and possibly even movement) of the target makes the probability of success for a longer-range shot too low. The same is true for conventionally-armed anti-ship cruise missiles. A nuclear warhead targeted against a city, though, faces no such limitations. Extreme long range is a pronounced advantage in a nuclear-armed cruise missile.

The pairing of a warhead type with a cruise missile airframe is not necessarily an exclusive process. The Tomahawk, for example, uses one common body to house four substantially different payloads. Close examination, however, of operational requirements such as design range and CEP, and

[7] Countervalue targeting is the employment of weapons, especially nuclear weapons, against items of intrinsic value to the opposing society (e.g., population centers, industrial facilities, etc.). Counterforce targeting implies use against the opposing force's military (especially nuclear) capability (e.g., ICBM silos and strategic bomber bases).

of design parameters such as size, weight and thrust, can reveal much about the intentions of the builder.

V BAYESIAN ANALYSIS: A METHODOLOGICAL TOOL

This paper has presented reasons why cruise missile proliferation and the transfer of missile technology are, or should be, matters of concern to the United States military and intelligence communities. It has summarized historical trends and described the state of the art of operational cruise missiles. Possible motivations for cruise missile acquisition or indigenous development have been explored, as have the specific technological capabilities required to build a modern, survivable and effective cruise missile.

It is now appropriate to look ahead. Given what is known about cruise missile systems and their proliferation, a systematic assessment and forecasting methodology is required. This methodology should be able to incorporate prior knowledge with new developments to answer a series of questions about cruise missiles:

1. What is the present state of development of country A's existing cruise missile program?

2. Is country B attempting to establish a cruise missile capability, through either acquisition or indigenous production?

3. What evidence supports the judgments rendered in response to questions one and two, above? What evidence refutes them?

The essential elements of any methodology proposed to answer such questions are evidence and systemization. Expert judgments by informed analysts remain the key to success in both analysis and forecasting, but even experts often disagree with one another. Such disagreements logically might arise in at least two ways: either the analysts are working from two different bodies of data, or they are interpreting the same datum points in different ways. The way to resolve such differences is to establish a system by which data are collected, sorted, and incorporated into a shared data base. This data base can then be used as evidence by an analyst to support his assessment. In this way, disagreements can be reduced to the meaning and relative weight to be assigned to a particular datum. Assumptions are forced to be *explicit*.

A. BAYESIAN ANALYSIS

One forecasting methodology which provides an explicit, quantifiable estimate of future conditions is known as Bayesian analysis. It derives from the work of the Reverend Thomas Bayes, a fellow of the British Royal Society. His formula, which dates to 1763,

> is a tool of statistical inference, used to deduce the probabilities of various hypothetical causes from the observation of a real event. It also provides a convenient method for recalculating those probabilities in the light of a continuing flow of new events....
>
> [T]he 'rule of Bayes' states that the probability of an underlying cause (hypothesis) equals its previous probability multiplied by the probability that the observed event was caused by that hypothesis. [Ref. 41:p. 12]

A simple example serves to illustrate the method. Suppose the weatherman on the evening news announces a 60 percent chance of rain by noon the next day. He awakens in the morning and observes that the sky is overcast and the barometer has fallen. He revises his forecast at 8:00 AM to read "75 percent chance of rain." By 10:00 AM, dark thunderclouds fill half the sky. At that point he assesses the chance of rain by noon to be 90 percent. How would Bayesian analysis be applied to computing these forecasts?

The hypothesis (H) to be proven is the occurrence of rain by noon the next day (call this outcome H1). The alternative hypothesis (H2) is that it will not rain by noon. The "prior probability" of H1 is the initial forecast of a 60 percent chance of rain (P(H1) = 0.60). The other hypothesis, of course, has a 40 percent probability (P(H2) = 0.40).[1]

For each new observation, or event (E), a series of judgments are made by the expert: what is the probability that this event would occur if the first hypothesis (H1) is true? If H2 is true? The product of each hypothesis' prior probability, P(Hi), and event probability, P(E/Hi) (the probability of E, given the truth of Hi), is then computed and the results, for all hypotheses, are added together.

The revised, or posterior, probability for any hypothesis, given the occurrence of the new datum point, can

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[1] There may be any number of alternative hypotheses, but they must be mutually exclusive and the sum of their probabilities must always add to unity.

then be computed by multiplying the prior probability of that hypothesis by the **ratio** between the event probability from that hypothesis and the previously computed summation.

Returning to the weather forecast, suppose that on 80 percent of days on which it rains by noon (in this particular location), the sky is overcast by 8:00 AM. Does this mean that the chance of rain is now (as of 8:00 AM on the day in question) 80 percent? No! It could be that the skies are also overcast here on 70 percent of the mornings that it does not rain by noon (or, for that matter, on 90 percent of them).

Applying the "rule of Bayes" to the occurrence, E, of an overcast sky at 8:00 AM, the products of each event probability and related hypothesis probability are computed and summed. P(H1), which is 0.60, is multiplied by P(E/H1), which is 0.80, to yield <u>0.48</u>. P(H2), or 0.40, is multiplied by P(E/H2), or 0.70, to yield <u>0.28</u>. The sum, 0.48 plus 0.28, is <u>0.76</u>.

The revised probability of rain by noon (H1) can then be calculated by muitiplying the prior probability (0.60) by the ratio of P(E/H1), 0.80, to the sum, 0.76. The resulting updated forecast is a 63 percent chance of rain by noon. The original 60 percent chance has been revised upward by a factor of (0.80/0.76).

While the above example is deliberately simple, more complex applications abound. The Central Intelligence Agency (CIA) began exploring the use of Bayesian analysis as a

forecasting tool in the mid-1970s with the personal support of then-CIA director William Colby [Ref. 41:p. 3]. The CIA used Bayesian analysis as an Indications and Warning (I&W) tool in order to assess the likelihood of hostilities in a number of different regional situations.* The results were, on the whole, encouraging. Although it is likely that "the narrative essay will remain the dominant form for intelligence estimates" within CIA, "[t]here is, however, an important role for rigorous procedures...in...complex estimative problems." [Ref. 41:p. 9]

When the CIA applied Bayesian analysis to the forecasting of politico-military events, they also incorporated another technique, known as Delphi. Developed by the RAND Corporation in the late 1940s, Delphi is a means to utilize the knowledge of a number of experts independently from one another. In the CIA's experience, Delphi and Bayesian analysis were highly complementary. [Ref. 42:p. 15]

The actual manner in which Bayesian analysis was applied at the CIA can be seen in the following example, which involved forecasting hostilities in the Middle East.

> On the first day of the period, each of a number of participating analysts submits the items of evidence he or she has seen since the last round which relate in any way to possible hostilities in the Middle East. The submission is in the form of one or two sentences

* These situations included, for example, the possibilities of a "North Vietnamese offensive during the dry season of 1974,...Sino-Soviet hostilities...and Arab Israel hostilities from Autumn 1974 to Summer 1976." [Ref. 42:p. 19]

summarizing the item, along with the date, source, and the classification.

The choice of data is left entirely to the analyst, who is instructed to include anything he considers relevant and to exclude what can be judged to be irrelevant. Later the same day, a coordinator consolidates the items, resolving differences of wording, emphasis, and meaning, and returns the complete list of items to all participants. The analysts, working individually, evaluate the items and return the numerical assessments the following day. This information is then collated and disseminated as an intelligence report. [Ref. 42:pp. 16-17]

In the experience of the CIA, Bayesian analysis was shown to have distinct advantages over more intuitive assessments. These advantages include:

(1) More information can be extracted from the available data...and probabilities are not at the mercy of the most recent or most visible item.

(2) The formal procedure has been shown to be less conservative than the analysts' informal opinions, and to drive the probabilities away from fifty-fifty faster and farther than the analysts' overall subjective judgments do....

(3) The procedure provides a reproducible sequence for arriving at the final figures....

(4) The formulation of the questions forces the analyst to consider alternative explanations of the evidence he sees...[and] to look at how well the evidence explains hypotheses other than the one he has already decided is the most likely.

(5) The use of quantified judgments allows the results of the analysis to be displayed on a numerical scale, rather than through the use of [subjective terms]. [Ref. 42:p. 24]

There are, however, "definite limitations" to the Bayesian forecasting technique.

(1) The question must lend itself to formulation in mutually exclusive categories....

(2) The question must be expressed as a specific set of hypothetical outcomes.

(3) There should be a fairly rich flow of data which is at least peripherally related to the question.

(4) The question must revolve around the type of activity that produces preliminary signs and is not largely a chance or random event. [Ref. 42:pp. 25-26]

From the advantages and limitations outlined above, the ways in which Bayesian analysis (with Delphi) can be applied to the problem of cruise missile proliferation can be deduced. For the purpose of forecasting, the hypotheses to be tested must be explicitly defined in mutually exclusive terms. For example:

1. By 1995, country A <u>will</u> possess a land-attack cruise missile capability; OR

by 1995, country A <u>will not</u> possess a land-attack cruise missile capability.

2. The cruise missile system being developed by country B will be:

A. a nuclear-armed land attack weapon, OR

B. a tactical land-attack weapon with a chemical warhead, OR

C. an anti-ship cruise missile with a high-explosive warhead.

3. The cruise missile system being considered for production in country C:

A. <u>will</u> be offered for export by 1994, OR

B. <u>will not</u> be offered for export by 1994.

In order to achieve satisfactory results, fulfillment of at least one of the hypotheses must require an adequate sequence of definable preliminary steps. Data relating to those events must be available. Whenever possible, a time horizon should be included. This horizon may be extended at will, but most data are time-sensitive to some degree, and should be reevaluated whenever the time factor is amended. [Ref. 42:p. 28]

While Bayesian analysis is intended to be a forecasting tool, there is an added benefit to its implementation. The information base required--raw data, sorted by country and by weapon system, with an analyst's qualitative remarks on source reliability and quantitative assessment of explanatory hypotheses--is an excellent reference source for any urgent demands for "snapshot" program evaluations (e.g., where is country A's missile program right now).

B. THE IMP DATABASE

Databases very similar to the one described above have already been created. One such database, operating at an unclassified level, is maintained at the Monterey Institute of International Studies (MIIS) in Monterey, California. It was established to support the International Missile Proliferation (IMP) Project, headquartered at the Institute.

1. Purpose

The purpose of the IMP, as stated in the introduction to its periodical publication, Missile Monitor,

is to collect, analyze and disseminate data and information on the motivations, capabilities, and patterns of trade of missile-proliferating states in the developing world. [Ref. 43:p. 2]

2. Sources

The IMP collects data from an expanding list of diverse sources. It receives on-line feeds from the wire services, including AP, UPI and Reuters. IMP also subscribes to all the major U.S. daily newspapers (e.g., New York Times, Washington Post, Los Angeles Times) and several foreign papers, as well. Additionally, the IMP subscribes to the Federal News Service, which assembles information released from the federal agencies (such as the Departments of State and Defense) and catalogues it by codeword (e.g., "nuclear," "missile"). The IMP staff searches all the major defense and military technology journals for data, as well as Foreign Broadcast Information Service (FBIS) products. As the users of the IMP database themselves have proliferated, another source of datum inputs has become available. Some of the users submit items which they come across in sources (such as foreign language newspapers) not routinely checked by the IMP staff. [Ref. 44]

3. Structure

Potential sources of data are screened by area specialists on the IMP staff. Specific items of interest are

coded[3] for entry into the database, and the screener prepares a narrative abstract of the reference material. He or she also has the option of entering qualifying comments or supplementary information. The resulting document (bibliographical reference, abstract, commentary and data codes) is reviewed for accuracy by another staff member and a supervisor before being assigned a sequential document number and keyed into the computerized database. [Ref. 44]

Information within the database may then be accessed by any of over 300 category codes or over 200 country or multi-country group codes [Ref. 45]. Abstracts of data sources, with bibliographic information, may be printed out by document number.

4. Applicability

The structure of the IMP database--its chronological, event-by-event format, its diversity of sources, and its detailed categorization and cross-referencing potential--makes it nearly a perfect foundation for the conduct of Bayesian analysis. A similar database, identically structured but cleared to contain both classified and unclassified information, would be ideal.

Applying the database to the problem of forecasting cruise missile proliferation or indigenous production, the following steps should be taken:

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[3] Examples of coding categories are country, weapon system, technological field, and interactive event (e.g., comment, denial, proposal, payment, delivery). [Ref. 45]

1. Define a specific set of mutually exclusive hypotheses, which include the outcome of concern and all logical alternatives. Define a specific time horizon.

2. Assign one or more subject-matter experts (area or technical specialists) to the problem.

3. Each analyst, independently, conduct a review of existing data and assign probabilities to each hypothetical outcome. These probabilities must sum to unity.

4. Each analyst, evaluate new events as they are added to the data base, assigning quantitative probabilities to the event with respect to each hypothesis.

5. Each analyst, compute the revised (posterior) probabilities, which then become the new prior probabilities, for each hypothesis.

6. Periodically compare the assessments of the individual analysts, identify major differences of opinion, resolve them if possible (and if desired), and report the range of forecasts regarding the subject of concern (with appropriate narrative explanation based on the evidence).

7. When appropriate, redefine the timeline and hypothetical outcomes and revise the prior probabilities of each hypothesis in light of all known data.

C. INDICATORS OF POSSIBLE CRUISE MISSILE DEVELOPMENT

With the existence of a database such as the one established for the International Missile Proliferation Project, it is already possible to apply Bayesian analysis to

the forecasting of cruise missile proliferation. Having described the method and the database, it is appropriate to conclude this section with a summary of specific datum points which would be relevant to the analysis of a nascent cruise missile program.[4]

1. Basic Science and Technology

- Aerodynamic design technology--for basic airframe design
- Computational fluid dynamics--for high-lift/low-drag designs
- Supercomputers--for airframe and warhead modeling
- Miniaturized computers--for onboard guidance and control
- Charge-coupled devices--for electro-optical imagery
- Analog-to-digital conversion devices
- Structural composites, laminates, and radar-absorbing materials

2. Airframe and Propulsion Technology

- Aerodynamic flight controls
- Liquid rocket motors
- Solid rocket motors and boosters
- Conventional jet propulsion systems
- Lightweight turbojet/turbofan/propfan engines
- Ramjet/scramjet[5] engines

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[4] The following list represents a composite summary of the body of this report. Sources most heavily drawn upon to provide individual items in the list are references 34 and 45.

[5] Scramjet: "[s(upersonic) c(ombustion) ramjet] a ramjet that burns its fuel in an airstream moving at supersonic speed." [Ref. 37:p. 1279]

- Surveillance, reconnaissance and target drones
- Remotely-piloted vehicles (RPVs)
- Missile propellants

3. Guidance Technology

- Preprogrammed autopilots and gyrocompasses
- Command guidance capabilities (i.e., radar/radio control)
- Passive radio frequency (RF) homing
- Passive infrared (IR) homing
- TV imaging/homing
- Laser homing
- Compact active radar systems
- Gyroscopic systems
- Ring laser gyroscopes
- Accelerometers
- Inertial navigation systems and software
- Radar altimeters
- Terrain mapping/TERCOM capability, or access to data
- Digital optical imaging
- Scene matching/digital scene matching area correlation (SMAC/DSMAC)
- GPS receivers

4. Warhead Technology

- Nuclear weapons capability
- Chemical weapons capability
- Biological weapons capability

- Advanced conventional weapons capabilities [e.g., fuel-air explosives (FAEs), cluster bombs]

- High-explosive warheads

- Safing, arming, fuzing and firing mechanisms [e.g., point-detonating, delayed point-detonating (i.e., penetrating), proximity]

5. Production and Testing Facilities/Capabilities

- Wind tunnel/aerodynamic flow field visualization chamber

- Radar cross section (RCS) measurement facility (especially one sized for cruise missile dimensions)

- Radar and/or optical tracking range for missile test flights

- Fixed-site missile launch facility

- Mobile missile launch facility [e.g., transporter-erector-launcher (TEL)]

- Cruise missile air-launch and/or sea-launch capability

- Missile or missile component production plants

6. Strategic, Diplomatic and Economic Factors

- Existence of military conflict or regional arms race

- Possession of cruise missiles by neighboring country

- Possession or pursuit of ballistic missiles or long-range strike aircraft by subject nation or its neighbors

- Stated missile import/export policies

- Membership in non-proliferation regimes, especially the Missile Technology Control Regime (MTCR)

- Budgetary constraints, foreign debt, and international balance of payments conditions

- Economic development programs in effect (e.g., import substituting industrialization, export substitution)

7. "Interactive"[6] Events

- Public or private comments by political, military or industrial leaders implying the necessity for cruise missiles, long-range weapons, advanced conventional weapons or weapons of mass destruction

- Meetings between representatives of nations which have such weapon systems, or supporting technologies, and nations which do not

- Contractual arrangements for the acquisition of applicable weapon systems or technologies (e.g., proposals, requests, refusals, negotiations, withdrawals, orders, payments or deliveries)

- Establishment of multinational programs for development or testing of missile systems, or shared use of testing facilities

8. Miscellaneous

- National budget allocations specifically related to cruise missile acquisition or development programs

- Observed cruise missile deployments, test flights, or actual employment in combat

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[6] Term used by IMP analysts to describe observable or reportable transactions related to weapons proliferation.

VI BAYESIAN ANALYSIS: A SAMPLE APPLICATION

This chapter presents a scenario to demonstrate the manner in which Bayesian analysis could be applied to cruise missile proliferation. This scenario is hypothetical; any resemblance to a specific developing nation is coincidental.

A. SCENARIO

It is January 1993. The nation of Parador is suspected of planning to develop an indigenous production capability for a long-range land-attack cruise missile armed with a chemical warhead.

Parador and its neighbor, Combatistan, are both emerging from a long period of colonial rule. They are both net importers of manufactured goods, relying on massive exports of raw materials (minerals and agricultural products) to maintain a stable but slightly negative balance of trade.

In recent years, Combatistan has developed a fairly large standing army backed by a capable close air support element. It has done so through the aid of certain European industrial nations that have mining interests in the region.

Ownership of a small but possibly valuable strip of mineral-rich land along the Paradori-Combatistani border is in dispute. Border incidents have flared up occasionally. It is obvious that Parador is militarily inferior to Combatistan.

The official position of the United States is neutrality. There is, however, a large population of expatriate Americans in Combatistan, most of whom are employees of multinational mining companies. The Americans are concentrated in the capital city of Miletus, which is located approximately 600 kilometers from the disputed border region.

The United States government is concerned that Parador will develop a long-range cruise missile system which could be used to deliver chemical warheads targeted against Combatistani population centers, including the capital, thereby placing the Americans there at great risk.

B. HYPOTHETICAL ALTERNATIVES

The following two hypotheses are proposed for testing:

1. Hypothesis H1: Parador <u>will</u> develop an indigenous production capability for a land-attack cruise missile armed with a chemical warhead by December 1994.

2. Hypothesis H2: Parador <u>will not</u> develop an indigenous production capability for a land-attack cruise missile armed with a chemical warhead by December 1994.

C. ESTABLISHMENT OF PRIOR PROBABILITIES

Parador area specialists and cruise missile technical experts make an initial assignment of probabilities based upon the following evidence:

1. Parador is a signatory of the Nuclear Non-Proliferation Treaty (NPT), but it has consistently refused to join any

other non-proliferation regime. According to the Paradori Foreign Minister, "we are a peaceful nation, uninvolved in such matters."

2. Parador has three large chemical manufacturing and processing facilities. Two of these facilities produce fertilizers and other commercial products for domestic consumption and export. The third facility is medicinal in nature. Parador denies any chemical weapon production capability or possession of any chemical weapon stockpiles.

3. Parador has a state-run final assembly plant for the production of small turboprop passenger aircraft and unmanned aerial vehicles (UAVs). Most of the manned aircraft are exported, but the UAVs are allocated predominantly for the small Paradori air force. The Paradori government is negotiating with the component-supplier nation for local licensed production of the airframe and engine components. Parador offers inexpensive labor in return for technical plans and advisory personnel.

4. Parador has no indigenous arms manufacturing capability. It imports all of its military hardware (except for the UAVs). It does, however, have a small explosives and ammunition factory adjacent to one of the fertilizer production plants. This factory produces small arms ammunition, land mines and artillery shells.

5. The Paradori military uses its fleet of UAVs for border surveillance and reconnaissance. These UAVs are radio-

controlled and equipped with TV cameras which feed video back to the controller on the ground.

After careful consideration of the situation in Parador, the team of analysts assigns the following prior probabilities:

1. P(H1): 0.35
2. P(H2): 0.65

The total of all probabilities sums to one, as it always must do.

Three analysts then are assigned to conduct independent Bayesian analyses on the developing situation in Parador, each analyst starting with the collectively determined prior probabilities. One analyst's event-by-event analysis is reproduced below.

D. EVENT-BY-EVENT BAYESIAN ANALYSIS

1. February 1993 (Source: Aviation Week & Space Technology): Parador signs licensed co-production agreement for aircraft engines and UAV airframes. Paradori Minister of Finance states need to start producing more manufactured goods for export.

P(H1):	0.35	P(E/H1):	0.65	P(H1) x P(E/H1):	0.228
P(H2):	0.65	P(E/H2):	0.60	P(H2) x P(E/H2):	0.390
				Sum:	0.618

Revised P(H1): 0.35 x (0.65/0.618) = 0.37
Revised P(H2): 0.65 x (0.60/0.618) = 0.63

2. February 1993 (Washington Post): The United States Congress, after heavy lobbying by the automotive industry and transportation firms, agrees to forbid the use of "Selective Availability" on GPS satellite transmissions. "Selective Availability" had been used by the United States military to intentionally degrade the accuracy of the GPS C/A signal.

P(H1):	0.37	P(E/H1):	0.50	P(H1) x P(E/H1):	0.185
P(H2):	0.63	P(E/H2):	0.50	P(H2) x P(E/H2):	0.315
				Sum:	0.500

Revised P(H1): 0.37 x (0.50/0.50) = 0.37
Revised P(H2): 0.63 x (0.50/0.50) = 0.63

3. April 1993 (classified source): Paradori military demonstrates an RF homing capability on a specially modified UAV.

P(H1):	0.37	P(E/H1):	0.60	P(H1) x P(E/H1):	0.222
P(H2):	0.63	P(E/H2):	0.25	P(H2) x P(E/H2):	0.158
				Sum:	0.380

Revised P(H1): 0.37 x (0.60/0.380) = 0.58
Revised P(H2): 0.63 x (0.25/0.380) = 0.42

4. May 1993 (Jane's Defence Weekly): Parador contracts to buy 300 combined INS/GPS systems from French firm Rafale.

P(H1):	0.58	P(E/H1):	0.60	P(H1) x P(E/H1):	0.348
P(H2):	0.42	P(E/H2):	0.50	P(H2) x P(E/H2):	0.210
				Sum:	0.558

Revised P(H1): 0.58 x (0.60/0.558) = 0.62
Revised P(H2): 0.42 x (0.50/0.558) = 0.38

5. September 1993 (Flight International): Parador establishes radar tracking range adjacent to national airport for flight testing of indigenously-produced UAVs.

P(H1):	0.62	P(E/H1):	0.65	P(H1) x P(E/H1):	0.403
P(H2):	0.38	P(E/H2):	0.50	P(H2) x P(E/H2):	0.190
				Sum:	0.593

Revised P(H1): 0.62 x (0.65/0.593) = 0.68
Revised P(H2): 0.38 x (0.50/0.593) = 0.32

6. September 1993 (classified source): Funding for Paradori military UAV program has tripled within a two-year span. The additional money has come from cuts in other military programs.

P(H1):	0.68	P(E/H1):	0.70	P(H1) x P(E/H1):	0.476
P(H2):	0.32	P(E/H2):	0.20	P(H2) x P(E/H2):	0.064
				Sum:	0.540

Revised P(H1): 0.68 x (0.70/0.540) = 0.88
Revised P(H2): 0.32 x (0.20/0.540) = 0.12

7. November 1993 (Jane's Defence Weekly): Rafale delivers 60 INS/GPS sets to Parador, promising 120 more within six months.

P(H1):	0.88	P(E/H1):	0.50	P(H1) x P(E/H1):	0.44
P(H2):	0.12	P(E/H2):	0.50	P(H2) x P(E/H2):	0.06
				Sum:	0.50

Revised P(H1): 0.88 x (0.50/0.50) = 0.88
Revised P(H2): 0.12 x (0.50/0.50) = 0.12

8. January 1994 (U.S. Defense Attache, Parador): Parador demonstrates a low-level, terrain-following capability in its UAVs. A UAV apparently was fitted with a radar altimeter and simple computerized flight controls.

P(H1):	0.88	P(E/H1):	0.80	P(H1) x P(E/H1):	0.704
P(H2):	0.12	P(E/H2):	0.60	P(H2) x P(E/H2):	0.072
				Sum:	0.776

Revised P(H1): 0.88 x (0.80/0.776) = 0.91
Revised P(H2): 0.12 x (0.60/0.776) = 0.09

9. January 1994 (Parador National Press Agency [ANPP]): Parador begins full-scale indigenous production of UAVs for commercial and military use and for export.

P(H1):	0.91	P(E/H1):	0.75	P(H1) x P(E/H1):	0.683
P(H2):	0.09	P(E/H2):	0.75	P(H2) x P(E/H2):	0.067
				Sum:	0.750

Revised P(H1): 0.91 x (0.75/0.75) = 0.91
Revised P(H2): 0.09 x (0.75/0.75) = 0.09

10. February 1994 (New York Times): In a nationally-broadcast radio address, Parador's President-for-Life announces that his country is a peace-loving nation but that it is prepared to defend itself if necessary.

P(H1):	0.91	P(E/H1):	0.40	P(H1) x P(E/H1):	0.364
P(H2):	0.09	P(E/H2):	0.90	P(H2) x P(E/H2):	0.081
				Sum:	0.445

Revised P(H1): 0.91 x (0.40/0.445) = 0.82
Revised P(H2): 0.09 x (0.90/0.445) = 0.18

11. April 1994 (U.S. Defense Attache, Parador): On National Day, Parador's military displays a mobile transporter/launcher/control facility for military reconnaissance UAVs.

P(H1):	0.82	P(E/H1):	0.80	P(H1) x P(E/H1):	0.656
P(H2):	0.18	P(E/H2):	0.30	P(H2) x P(E/H2):	0.054
				Sum:	0.710

Revised P(H1): 0.82 x (0.80/0.71) = 0.92
Revised P(H2): 0.18 x (0.30/0.71) = 0.08

12. April 1994 (Reuters): The commanding general of the Paradori military, speaking at a National Day parade, threatens "dire consequences" if Combatistan tries to occupy the disputed territory.

P(H1):	0.92	P(E/H1):	0.70	P(H1) x P(E/H1):	0.644
P(H2):	0.08	P(E/H2):	0.40	P(H2) x P(E/H2):	0.032
				Sum:	0.676

Revised P(H1): 0.92 x (0.70/0.676) = 0.95
Revised P(H2): 0.08 x (0.40/0.676) = 0.05

13. June 1994 (Parador National Press Agency, front page): In a large-scale military exercise, the Paradori military demonstrates their capability to deploy, launch and control two dozen UAVs with effective two-way exchange of command and control information between the individual UAV launchers and the central military command.

P(H1):	0.95	P(E/H1):	0.90	P(H1) x P(E/H1):	0.855
P(H2):	0.05	P(E/H2):	0.10	P(H2) x P(E/H2):	0.005
				Sum:	0.860

Revised P(H1): 0.95 x (0.90/0.86) = 0.99
Revised P(H2): 0.05 x (0.10/0.86) = 0.01

On 01 July 1994, in response to the increasing tensions between Combatistan and Parador, the Paradorian cruise missile action team (PCMAT) is reassembled and each analyst presents the results of his or her Bayesian forecasting procedures. While there is some disagreement on the precise numerical value, each member of the team concurs that there is a high probability that Parador has, or soon will have, a land-attack cruise missile capability. The evidence is insufficient to determine whether the missile will be fitted with a chemical warhead or whether the Paradori government has the will to use such a weapon.

E. CASE STUDY LESSONS LEARNED

Several valuable insights can be gleaned from the scenario which unfolded above. Bayesian analysis is a forecasting tool, not a panacea. It is intended to be used in conjunction with other analytical methods, including (especially!) the sound judgment of subject matter experts.

The qualitative value of the probabilities generated by the technique is utterly dependent on the soundness of the underlying hypotheses and on the analyst's ability to assign meaningful probabilities to events as they unfold. Some aspects of intelligence analysis undoubtedly are not amenable to this type of quantification. It is the responsibility of the intelligence professional to make this determination.

What does it mean for the hypothetical analyst to arrive at a 99 percent probability that the first hypothesis is valid? It means only that the overwhelming preponderance of the evidence available tended to support that hypothesis more strongly than it did the alternative hypothesis. Each time an analyst assigns a higher event probability [P(E/H)] to H1 than to H2, the posterior probability of H1 will increase.

In the example above, the trend of the numerical values is probably more important than the numbers themselves. The real value of the quantification should emerge when the analysts sit down together to compare notes. Do they all agree on the trend? Do they agree about which events caused the greatest shifts in the relative likelihood of each hypothesis? It is in answering these questions that the discipline of numerical evaluations should pay the greatest dividends.

VII CONCLUSIONS AND IMPLICATIONS

A. SUMMARY

Bayesian analysis is one of many techniques available for intelligence assessments and forecasting. Its principal advantage is the quantification of potentially vague verbal expressions by the formulation of alternative hypotheses and the estimation of probabilities relating these hypotheses to observed consequences. The success of the method depends primarily upon the ability to devise realistic, comprehensive hypothetical causes and to assign meaningful probabilities to these causes upon the observation of pertinent events. Such abilities require in-depth, even expert, knowledge of the subject which is the focus of the analysis.

With respect to cruise missiles, pertinent topics for any Bayesian analyst include the historical development of such weapons (for better perspective); the many, sometimes conflicting motives which drive weapons procurement programs; and the particular technologies (e.g., stealth, propulsion, and guidance systems) which are essential to construction of a modern cruise missile. Each of these topics has been addressed in a section of this report.

To successfully use Bayesian analysis, it is essential to understand the Bayesian technique, and to appreciate the strengths and potential drawbacks of the technique,

specifically when it is applied to political and military forecasting problems. These issues were explored in the two preceding sections.

B. IMPLICATIONS

A larger question remains unanswered. Suppose Bayesian analysis proves to be an effective means of projecting the direction of weapons development programs in general, and of a cruise missile program in particular. How can this information be utilized by national-level policymakers to help guide them in their decision-making processes?

Upon the determination that another country is developing a threatening cruise missile capability, the United States government has a number of alternatives. It may impose unilateral export controls in an attempt to limit the diffusion of exclusively American technology. More effectively, the U.S. government can initiate or enter into multilateral non-proliferation agreements (such as the Missile Technology Control Regime (MTCR), which the United States joined in April 1987).

The United States also has the option of pursuing more energetic strategies. If selling, buying or building cruise missiles solves a particular problem for a nation, then perhaps the United States can offer another, less threatening or destabilizing solution. This solution may take the form of increased aid for economic development, entry into a bilateral security pact, or arbitration of a long-standing

regional dispute. By enabling early identification of a proliferant's course of action, and by suggesting the root causes for such action, Bayesian forecasting and the complementary Delphi method mentioned previously might serve well the interests of the United States government.

A final policy option is available in those instances in which moral suasion and mutual self-interest have failed to prevent the development of dangerous weapon systems. If another nation successfully mates a weapon of mass destruction (e.g., a nuclear or chemical warhead) with an effective delivery vehicle, such as a reliable, survivable cruise missile, then drastic action may be deemed necessary. A preemptive military strike may be ordered to neutralize one or more aspects of the newly-developed offensive capability.

Such an aggressive action as a preemptive strike has profound moral, legal and diplomatic ramifications. It is something to be avoided, if possible. While a Bayesian analysis or other forecasting tool might uncover the evidence which leads to a preemptive strike, it is the author's hope that precise and accurate intelligence forecasting can help obviate the need for such reactionary policy choices.

C. RECOMMENDATIONS FOR FURTHER RESEARCH

This report has introduced the concept of applying Bayesian analysis to forecast cruise missile proliferation. It is by no means a definitive study. Several avenues of additional research present themselves:

1. **Expand and elaborate the list of indicators** of cruise missile development, using historical cases to provide guidance for the quantification of event probabilities.

2. **Perform a Bayesian analysis of an actual, completed (or nearly completed) case** of cruise missile proliferation or indigenous production. Target nations for such studies include (but are not limited to) China, North Korea, Israel, South Africa and Taiwan.

3. **Establish an ongoing real-time Bayesian analysis** for a specific, nascent cruise missile developer.

4. **Define more precisely the nature of hypotheses** which may be applied to cruise missile forecasting problems and are amenable to the Bayesian method.

5. **Conduct a comparative analysis** of Bayesian forecasting and other methods presently used by the United States intelligence community.

Cruise missiles and the technologies required to produce them are not going away. It is likely that they will continue to proliferate. One purpose of intelligence forecasting, including the technique described herein, is to ensure that the United States government is not surprised by such developments. Bayesian analysis represents one promising method to minimize or avoid surprises; there are certainly others. With consistent application, the "rule of Bayes" can become a powerful implement in the professional intelligence analyst's toolkit.

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